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ABSTRACT

We describe a design for producing a soft x-ray laser via 3p-3s transitions in Ne-like Selenium (wavelength of about 200 Å). A 0.53 μm laser, focused in a 1.2 x 0.02 cm spot to mid 10^{13} W/cm^2 heats and burns through a thin foil of Se. Besides ionizing the Se to a Ne-like state, the laser explodes the foil, creating a flat electron density gradient. This allows propagation of the x-rays down the 1 cm long gain direction without debilitating refraction. Gains of 4 to 10 cm^{-1} are predicted for various transitions.

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For ions in the neon isoelectronic sequence, the rates for electron collisional excitation from the $1s^2 2s^2 2p^6$ ground-state configuration to $1s^2 2s^2 2p^5 3p$ are greater than the rates for excitation from the ground state to $1s^2 2s^2 2p^5 3s$. Whereas the $2p^5 3p$ J=0 levels are populated by direct monopole excitation from the ground state, other $2p^5 3p$ levels such as J=2 are fed primarily by cascades from upper levels and recombination from F-like ions. Dipole radiative decay of the $2p^5 3p$ levels to the ground state is forbidden, while the $2p^5 3s$ J=1 levels radiatively decay very rapidly, leading to population inversion between the 3p and 3s levels. (See Fig. 1). For electron densities and temperatures that are typical of laboratory laser produced plasmas, calculations[1-10] have shown that under favorable conditions large soft x-ray laser gains and amplification can be achieved.

From theoretical considerations[9], the most promising elements in which to implement this electron collisional excitation scheme, given a 0.53 μm laser at 10^{14} W/cm^2, occur near Z=36. Therefore solid Se (Z=34) was chosen as a candidate lasant. Elements much lower in Z tend to overionize, and those with higher Z have smaller 2-3 excitation rates. Reference 9 describes the predicted high gains at 183 Å $((2p^5_{1/2}\ 3p_{1/2})_{J=0}$ to $(2p^5_{1/2}\ 3s_{1/2})_{J=1})$ when 0.53 μm light, line focused at an intensity of 10^{14} W/cm^2 illuminates solid Se. In this approach, the high gain region occurs along the steep density gradient caused by the laser heated blowoff from the Se surface. The lack of an observed signal in previous experiments[11] was attributed[9] to refraction which bends the x-rays out of the high gain region (thus preventing significant amplification) and out of the line of sight of the diagnostic instruments. The refraction is due to the steep density gradient.

In this paper we present a technique designed to minimize the refraction problem while still producing plasma conditions suitable for lasing. The target is a thin Se foil, typically 750 Å deposited on 1500 Å of Formvar (Polyvinyl Formal: $C_{11}H_{18}O_5$) for structural integrity. The 0.53 µm laser is focused via a cylindrical lens to a 1.2 cm long by 0.02 cm wide region of the foil. As described in detail below, the foil explodes as the laser burns through it, creating a rather flat electron density profile in the plasma that has expanded into a roughly cylindrical shape. The smooth profile allows the x-ray laser beam to proceed straight down the long line focus direction, stay within the region of high gain, and propagate into the narrow angle of acceptance of the diagnostics. Exploding foils have previously been used[12] to create large scale-length plasmas to study laser driven parametric instabilities.

There are two main tools employed in the design of the foils. The 2-D hydro code LASNEX[13] simulates the laser-foil interaction, including absorption, burn-through, and hydro motion. It has been exercised with great success in dealing with other high Z, non LTE, laser created plasmas.[14,15] Quantities such as the time evolving electron and ion temperatures, densities and flow fields are then fed into the 2-D x-ray laser code XRASER[5]. XRASER uses this hydro input, along with detailed atomic data (such as level energies, radiative and collisional rates) computed off-line, to calculate atomic level populations and gain as a function of space and time. The atomic model includes in detail all the singly excited states of the Ne-like and Na-like ions with n=3 & 4 and F-like ions with n=2 & 3. Simpler models were used for the other sequences and levels. For the n=2 to 3, 4 transitions collisional excitation cross sections were computed using a multiconfiguration relativistic distorted wave code.[16] Line transfer is computed in 1-D and 2-D including the effects of partial redistribution andd bulk doppler shifts, using a modified S_n (ray) algorithm with a linearized ETLA convergence scheme. In particular, trapping between the ground state and the 3s and 3d levels are included, as they can affect the predicted gain to a moderate degree. A post-processor SPECTRE produces a predicted spectrum for any particular line of sight, including (in 1-D) refraction effects, to facilitate direct comparison with experimental data.

The design goal is to produce a flat electron density (n_e) and temperature profile, with scale length L of at least 100 microns, to last at least 100 ps, with high enough n_e (mid 10^{20} cm^{-3}) for appreciable density of neon-like ions and gain. These numbers are motivated by simple considerations. For a linear density gradient, $n_e = n_o (1-(y/L))$, with the usual plasma dispersion relationship $\omega^2 = \omega_p{}^2 + k^2 c^2$, an x-ray propagating in the x direction has $k_x=(\omega/c)(1-d)^{1/2}$ where $d=\omega_{po}{}^2/\omega^2=1/2500$ for $n_o=10^{21}$ cm^{-3} and a 50 eV x-ray. Thus $x=ct(1-d)^{1/2}$. Since $k_x=(k^2-k_x^2)^{1/2}$, and the group velocity is c^2k/ω, we obtain $dy/dt = c^2k_y/\omega$, leading to $y=c^2t^2d/4L$ or $y=x^2d/4L$. For a typical 10 milliradian divergence and acceptance angle of the spectrograph, and an x = 1 cm line focus, y = 0.01 cm, which leads to the L = 0.01 cm requirement. The transit time for the x-rays down the 1.2 cm is about 40 ps, which leads to the requirement of a 100 ps or so duration of the plasma.

The Novette laser at LLNL can provide 2 beams, each with a 1.2 cm x 0.01 cm line focus, and an intensity of up to 2 x 10^{14} W/cm^2. A 2-sided illumination of the foil (1 beam per side) is employed in an attempt to compensate for random non-uniformities in any one beam that could lead to refractory density nonuniformities in the lasing medium. However, as will be shown below, even a 1 beam illumination is sufficient to explode the foil nearly symmetrically, so that with a sufficiently smooth beam profile it too would be an acceptable illumination scheme.

Experiments were performed at KMS Fusion, Inc., to test the LASNEX & XRASER modeling of the exploding foil, using a single beam of 0.53 μm laser light. A 0.26 μm probing laser produces 20 ps snapshot holographic interferograms which can be inverted to indicate density profiles of the plasma.[17, 18] In Fig. 2 we see the results from a 5 x 10^{13} W/cm^2, 360 ps flat-topped illumination of a Se on Formvar foil, probed about 100 ps after the end of the pulse. The LASNEX simulation matches the data fairly well. Note the nearly symmetric profile despite the single sided illumination, and the flat n_e profile over the requisite 100 micron distance. We have no data, however, on turbulence that may affect the density profile on the scale of 1 μm or shorter. The code's predictions track the profile data over large variations in intensity, pulse length, and probing times, leading to substantial confidence in this aspect of the modeling.

Obtaining precise measurements of the electron temperature, T_e of the exploding foils is a much more difficult task. An inference of it can be made by observing the backscattered light (135^o from the incident laser's k vector) at wavelengths between 0.53 and 1.06 μm. The detected spectrum is interpreted[19] in terms of stimulated Raman scatter (SRS). The short wavelength cutoff of this SRS spectrum is usually quite sharp, and is attributed to Landau damping at $k_e\lambda_D$ = 0.3, where k_e is the wavenumber of the electron-plasma wave, and λ_D is the Debye length. In the Novette experiments on the actual x-ray laser thin foil targets, most of the data show spectral cutoffs ranging from 0.67 to 0.70 microns, leading to estimates of peak T_e in the 700 to 1000 eV range. This is in rather close agreement to the predicted T_e of 900 eV. (The ion temperature is predicted to be about 400 eV). In addition dot spectroscopy[20,21], using the Si Ly_e to He_e ratio as a T_e diagnostic, has been used to infer the plasma temperature in Se-disk experiments at KMS. Preliminary analysis indicates that the results are in good agreement with the predictions of LASNEX.

Given the densities and temperatures from LASNEX, XRASER predicts the fraction of Se in various ionization states. While most of the excitation and ionization rates and their inverses are calculated from first principles[5], dielectronic recombination is modeled in a crude way, albeit with plausible gross rates of low to mid 10^{-11} $cm^3 sec^{-1}$. (We are currently hampered in this regard by the paucity of data for recombination from F-like sequences near Z = 34, and by the low-density limit in which dielectronic recombination rates are usually calculated, a limit not relevant to our system.) The SPECTRE post-processor code yields a theoretical 3s-2p and 3d-2p spectra (from Ne-like and F-like states) which is compared to one obtained from a KMS experiment. In this case the thin foil was illuminated with a 1 mm line focus at 5×10^{13} W/cm^2 and the data is time resolved, but spatially integrated over the exploding foil. (Fig. 3). Since the n_e and T_e profiles are quite uniform, the spatial integration does not severely compromise the data. The 3d-2p parts of the spectrum show rather good agreement with the theory, though the modeling perhaps overpredicts the F-like fraction by a moderate amount. The simulations predict about 25% of the Se to be Ne-like, and about 40% F-like. The 3s-2p lines are quite a bit stronger than the theory's predictions.

We now discuss the detailed level populations and predicted x-ray laser gains. Figure 4a shows the predicted gain isocontours for the J=0 to 1 transition at 183 Å. Only the Se part of the Se/Formvar foil is displayed, hence the apparent asyymetric plasma. This foil was irradiated at 4×10^{13} W/cm^2 for 450 ps. The gain at the peak of the pulse is about 10 cm^{-1}. Before the peak of the optical laser pulse the foil has not burned through and refraction interferes with the x-ray propagation. By about 200 ps after the peak of the pulse the foil has expanded and cooled significantly. The lowered density contributes to a falling gain, as does the drop in monopole excitation rate due to the cooling. Figure 4b shows the predicted gain for a J=2 to 1 transition $((2p^5{}_{1/2}\ 3p_{3/2})_{J=2}$ to $(2p^5{}_{1/2}\ 3s_{1/2})_{J=1})$ at 209 Å. It is about 4 cm^{-1} in the flat non-refractory region of the plasma. The gain stays slightly more constant in time for the J=2 lines, since those levels are fed by cascading from higher levels during the cooling phase. Similar gains are predicted for the $((2p^5{}_{3/2}\ 3p_{3/2})_{J=2}$ to $(2p^5{}_{3/2}\ 3s_{1/2})_{J=1}))$ transition at 206 Å.

The measured gains are described in the companion paper.[22] While the J=2 to 1 transitions exhibit amplification with a gain coefficient of about 5 ± 1 cm^{-1}, within 50% of our predictions here, the J=0 to 1 transition is not observed to amplify to any great degree, and certainly not within an order of magnitude of the predicted 10 cm^{-1}. The time behavior of the J=2 to 1 lasing lines follows the theory rather closely, lending credence to the physical picture presented above. The agreement of the J=2 gain to within 50% of the theory is as good as we can reasonably expect, given our uncertainties in n_e, T_e, and in the fraction of the Se in the Ne-like state. It is of interest to note that the J=2 to 1 transitions at 206 and 209 Å are both calculated and measured to have nearly equal gains. This equality appears to be remarkable coincidence and should not necessarily be expected in other systems. We have computed gains on other 3p-3s transitions in the Ne-like sequence (at 220 Å and 263 Å) as well as on 3-3 monopole excited transitions in F-like sequence (at 204 Å). While the predicted Ne-like transitions are observed to have some gain[22], there is no experimental indication of amplification for any F-like lines, even at high laser irradiation.

There are many speculations as to the absence of the J=0 to 1 laser. The collisional excitation rate directly into the state has been calculated by numerous authors[5,7,10,23] and all agree fairly closely. Extra recombinative processes may be feeding the lower (3s) levels as well as the J=2 3p levels (with their higher statistical weight relative to the lower J levels), thus maintaining the J=2 inversion while destroying the J-0 one. This scenario harkens back to the high 3s-2p emission discussed earlier. In another vein, the simplest way of all to destroy the J=0 upper state population is to find mechanisms that mix the 3p manifold such that all the sublevels are populated according to their statistical weights (the sublevels are less than 10 eV apart, and are in a 1 keV plasma). We have not identified the actual mechanisms to date. Protons (from the Formvar substrate) colliding with the Se ions do not seem to be sufficient. In fact, a shot with only 250 Å of Formvar substrate (vs. the usual 1500 Å) improved the J=2 gain somewhat, but still failed to show any significant J=0 signal. Varying Z did not produce the missing laser either, thus virtually ruling out coincidental absorption resonances. Since the J=0 level is so strongly connected to the ground state, another possible mechanism for depleting it may be electron capture. Consider a state with an electron already in the 3p J=0 level. Electron capture promotes another electron from the L-shell into a higher lying Rydberg level. The principal decay mode of this 3-excited-electron state is the transfer of the 3p electron to the L-shell, release of the captured free electron, and the eventual cascade of the previously promoted L-shell electron back down to lower levels, quite possibly the J=2 levels. This mechanism thus depletes the J=0 level, and possibly feeds the J=2 levels as well. It is our hope that future experiments, and subsequent theoretical progress will shed some light on this scenario, or others that may arise.

Shorter wavelength lasing can be achieved with analogous transitions in higher Z elements, as has been demonstrated with Yttrium.[22] However we note that we need not concentrate solely on Ne-like systems in the future. We believe that Ni-like states (using higher Z elements) can also lead to lasing[24] of the type discussed here, possibly with higher gain, and almost certainly at shorter wavelengths.

In summary, data from holography, Si-dot and Raman spectroscopy, and 3-2 Se spectroscopy, give us some confidence that the exploding foil plasma has been prepared in roughly the way the modeling would predict. To produce gain, amplification and propagation we have created a flat n_e (5×10^{20} cm^{-3}) and T_e (1 keV) profile, with a substantial fraction of the Se in a Ne-like state. Gain predictions for the J=2 to 1 transitions are within 50% of the observations, but we can only speculate as to the fate of the missing J=0 to 1 transition.

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FIGURE CAPTIONS

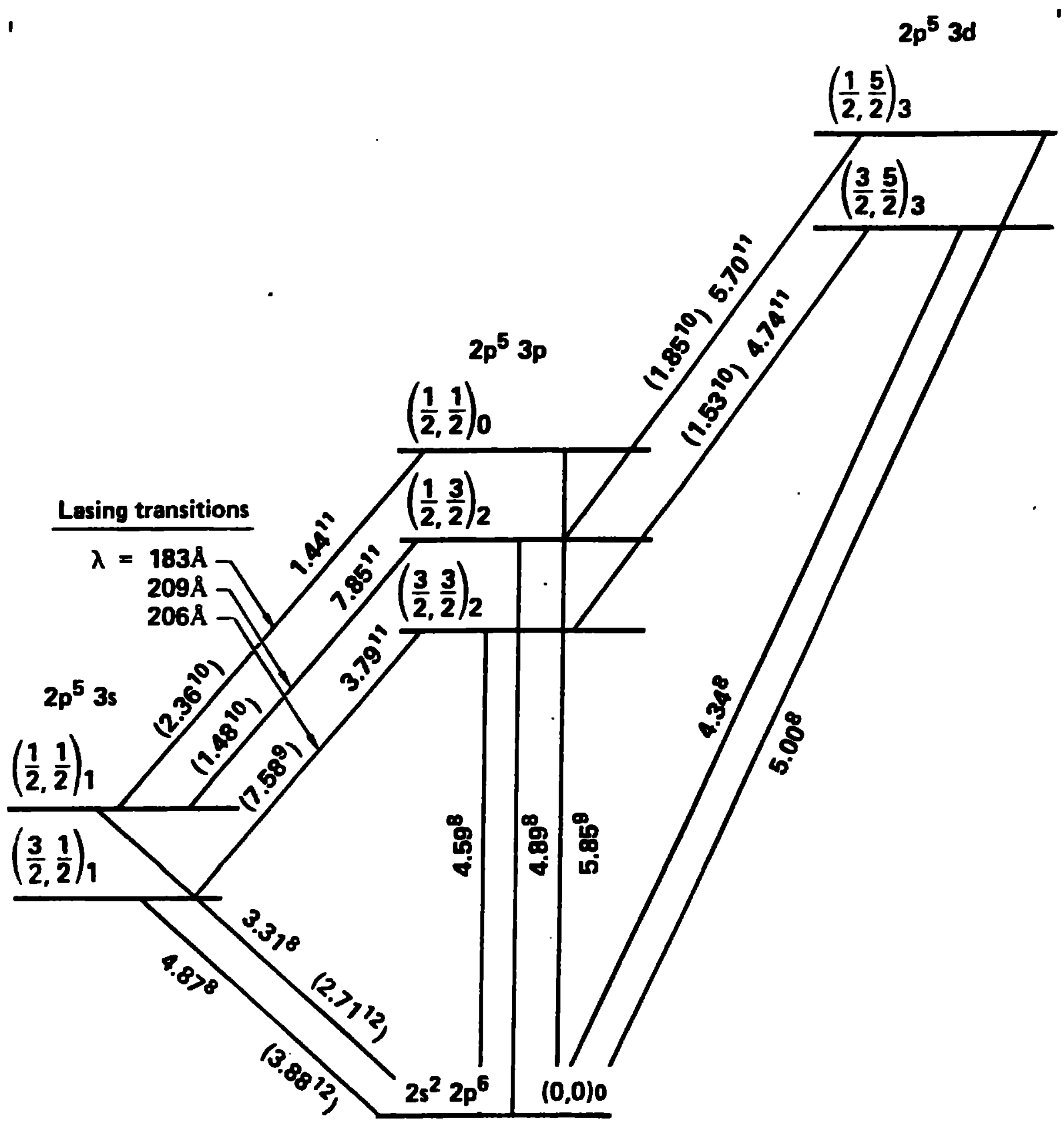
Figure 1. Simplified energy level diagram ($(j_1,j_2)_J$ notation) for Ne-like Se. Shown are only 8 out of the hundreds of levels that are included in the calculations. Collisional excitation rates and radiative decay rates (in parentheses) for $n_e = 5 \times 10^{20}$ cm^{-3} and $T_e = 1$ keV are shown.

Figure 2. a) Experimental set-up for, and example of, holographic interferometry.

b) Comparison of LASNEX simulation (solid line) and electron density profile (+) inferred from the Abel inversion of the interferogram from a).

Figure 3. Comparison of experiment (a) and theory (b) for the time resolved 3-2 spectra of Se. Darkened lines are Ne-like, and undarkened lines are F-like. Time is near the peak of the pulse. Lines above 8 Å are 3s-2p, and below 8 Å are 3d-2p.

Figure 4. Isocontours of gain for a) J = 0 to 1 182 Å line and b) J = 2 to 1 209 Å line. Central contour has gain = 10 cm^{-1} in a) and 4 cm^{-1} in b). Outer contours drop off by a factor of 0.8 each.



2p5 3d
(1/2, 5/2)3
(3/2, 5/2)3
2p5 3p
(1/2, 1/2)0
(1/2, 3/2)2
(3/2, 3/2)2
Lasing transitions
λ = 183Å
209Å
206Å
2p5 3s
(1/2, 1/2)1
(3/2, 1/2)1
1.44 11
(2.36 10)
7.85 11
(1.48 10)
3.79 11
(7.58 9)
(1.85 10) 5.70 11
(1.53 10) 4.74 11
4.59 8
4.89 8
5.85 9
4.34 8
5.00 8
3.31 8
(2.71 12)
4.87 8
(3.88 12)
2s2 2p6
(0,0)0

Fig. 1

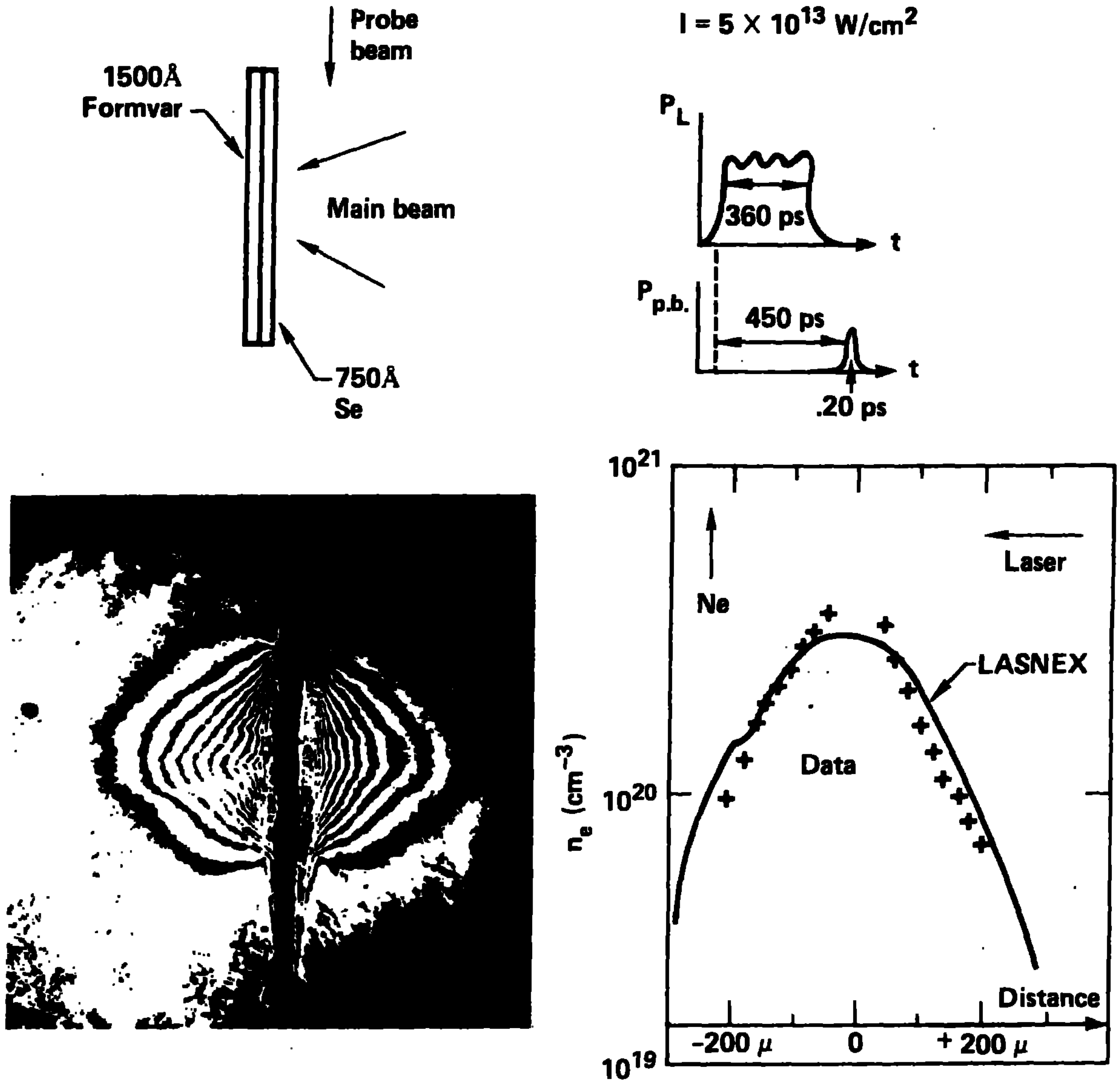

Probe beam
1500Å Formvar
Main beam
750Å Se
$I = 5 \times 10^{13}$ W/cm^2
P_L
360 ps
t
$P_{p.b.}$
450 ps
t
.20 ps
10^{21}
Ne
Laser
LASNEX
Data
n_e (cm^{-3})
10^{20}
Distance
-200 μ
0
+ 200 μ
10^{19}

Fig. 2

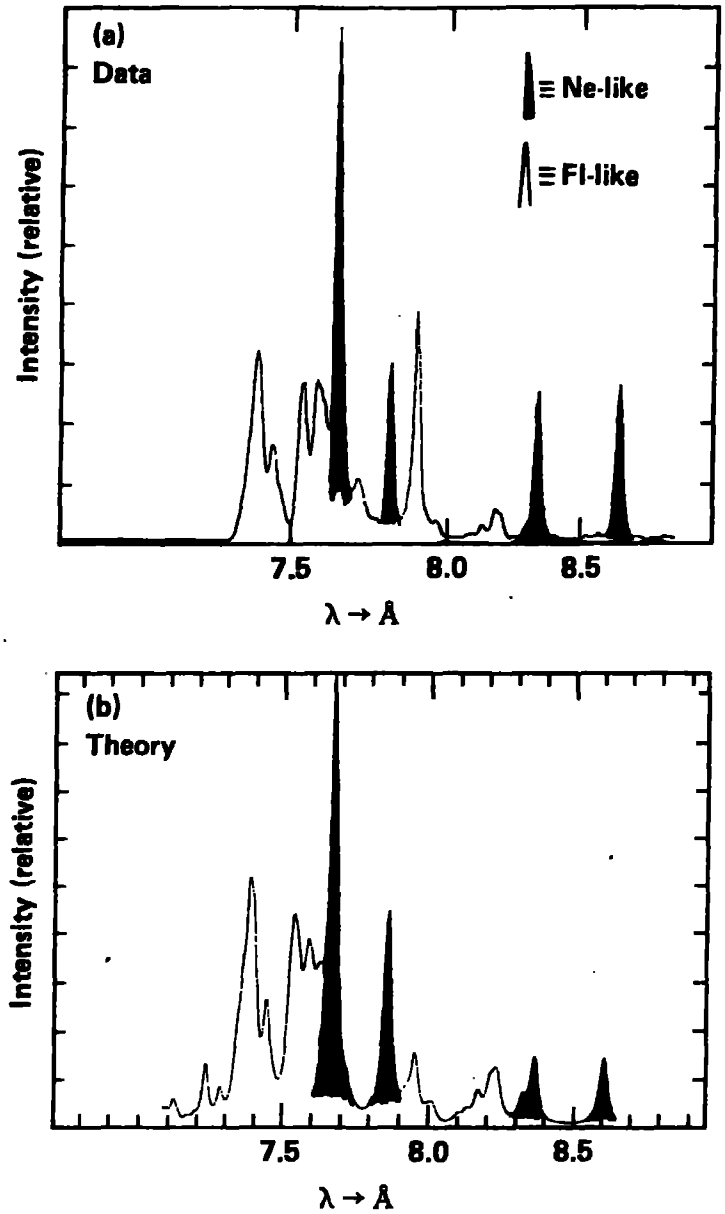

(a)
Data
≡ Ne-like
≡ Fl-like
Intensity (relative)
7.5
8.0
8.5
λ → Å
(b)
Theory
Intensity (relative)
7.5
8.0
8.5
λ → Å

Fig. 3

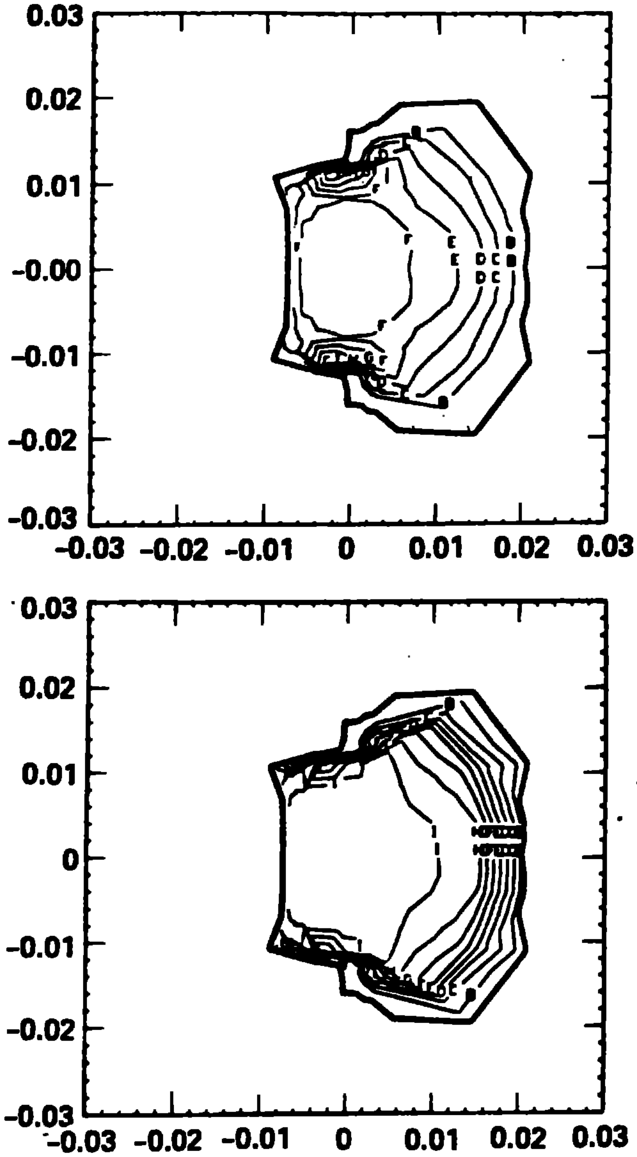

0.03
0.02
0.01
-0.00
-0.01
-0.02
-0.03
-0.03 -0.02 -0.01 0 0.01 0.02 0.03
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.03 -0.02 -0.01 0 0.01 0.02 0.03

Fig. 4